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Consumptive water use associated with food waste: case study of fresh mango in Australia

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Abstract

In many parts of the world, freshwater is already a scarce and overexploited natural resource, raising concerns about global food security and damage to freshwater ecosystems. This situation is expected to intensify with the FAO estimating that world food production must double by 2050. Food chains must therefore become much more efficient in terms of consumptive water use. For the small and geographically well-defined Australian mango industry, having an average annual production of 44 692 t of marketable fresh fruit, the average virtual water content (sum of green, blue and gray water) at orchard gate was 2298 l kg⁻¹. However, due to wastage in the distribution and consumption stages of the product life cycle, the average virtual water content of one kg of Australian-grown fresh mango consumed by an Australian household was 5218 l. This latter figure compares to an Australian-equivalent water footprint of 217 l kg⁻¹, which is the volume of direct water use by an Australian household having an equivalent potential to contribute to water scarcity. Nationally, distribution and consumption waste in the food chain of Australian-grown fresh mango to Australian households represented an annual waste of 26.7 GJ of green water and 16.6 GJ of blue water. These findings suggest that interventions to reduce food chain waste will likely have as great or even greater impact on freshwater resource availability as other water use efficiency measures in agriculture and food production.

1 Introduction

The world faces a food security challenge of massive proportion. Currently, there are an estimated 963 million undernourished people in the world, representing about 15% of the total population (FAO, 2008a). Yet demand for food is also forecast to double by 2050 based on projected population and socio-economic growth (FAO, 2008b). While agricultural yields have shown impressive increases over the twentieth century, largely due to genetic improvements, irrigation, fertilization and the use of pesticides, envi-

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ronmental sustainability has in many locations been compromised (Nellemann et al., 2009). One of the greatest constraints on current and future food production is the availability of freshwater, which is now a scarce and overexploited resource in many parts of the world (Bartram, 2008; Falkenmark, 2008). The Aral Sea tributaries, Chao
5 Phraya, Colorado, Ganges, Huai, Indus, Jordan, Lake Chad tributaries, Murray, Nile, Rio Grande and Yellow are among a growing list of rivers where consumptive water use by agriculture has reduced flows severely, in some cases causing flows to become intermittent in the lower reaches (Falkenmark and Lannerstad, 2005). The Punjab
10 province of Pakistan, the Gujarat and Rajasthan states of India, and the North China Plain are but a few of the major food producing regions where groundwater is being extracted at unsustainable rates (Falkenmark and Lannerstad, 2005).

Consumptive water use refers to the removal of water from a local hydrological system, thereby rendering it unavailable for further use (Falkenmark and Lannerstad, 2005; Liu et al., 2009). That is, there is no verifiable return flow. Present consump-
15 tive water use for global food production has been estimated at between 16 950 and 18 600 km³ yr⁻¹ (Rockström et al., 2007, 2009) consisting of around 35% green water consumption by rainfed croplands, 10% blue water consumption by irrigated croplands and 55% green water consumption by pastures. These results are broadly consistent with separate estimates of 3823 km³ yr⁻¹ of consumptive water use for 17 major
20 crops representing 63% of global cropland area, with 81% being green water (Liu et al., 2009). Blue water is derived from surface and groundwater sources whereas green water is derived directly from natural rainfall over agricultural lands. These figures highlight the dominance of green water in current global food production, even though irrigation accounts for around 70% of all freshwater withdrawals (UNESCO-WWAP,
25 2006). However, what is alarming from both a food security and environmental sustainability perspective is that at current rates of agricultural water use efficiency, an estimated additional 5700 km³ yr⁻¹ of freshwater will be needed to meet the demand for food in 2050 (Rockström et al., 2009). Since the availability of additional blue water resources is limited, a range of strategies have been proposed for achieving future food

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security. These include the continued conversion of natural ecosystems to new agricul-
tural lands to access greater volumes of green water, water productivity improvements
in agriculture (i.e. so-called crop per drop improvements), shifting diets to minimise
the consumption of animal products which have high consumptive water requirements,
5 water saving through increasing trade in agricultural commodities, and reducing food chain losses (Rockström, 2003; Chapagain et al., 2006a; Yang et al., 2006; Lundqvist
et al., 2007; Rockström and Barron, 2007; Rockström et al., 2007, 2009; Yang and Zehnder, 2007; Liu and Savenije, 2008; Liu et al., 2008; Nellemann et al., 2009).

Regarding food chain losses, it is commonly believed that these are in the order of
10 30 to 50% between farm and fork (Henningsson et al., 2004; Kader, 2005; Bloom, 2007; Lundqvist et al., 2008; Meeusen and Hagelaar, 2008), although detailed characterisation is lacking in Australia (Morgan, 2009) and elsewhere. Substantial variation from one food chain to another is likely. Broadly speaking, a contrast exists between developing countries where losses tend to be high toward the beginning of the food
15 chain due to poor harvesting, storage and transport, and developed countries where losses in wholesaling, retailing and consumption often predominate (Lundqvist et al., 2008). This is due to the expectation by consumers in developed countries for produce in perfect condition and a tiny blemish or deviation from optimal ripeness can exclude a product from consumer consideration. In describing food waste, a distinction must
20 also be made between avoidable food waste, representing food that could have been eaten, and unavoidable food waste, representing bones, peel, pips and stones and the like which are generally inedible, but nonetheless may have other beneficial uses.

Supply chain waste, from farm to consumer, naturally represents a cost to the firms involved in terms of unrealised sales, excessive raw material usage and disposal costs
25 (Henningsson et al., 2004; Pagan and Prasad, 2007). However, the effort and expense associated with reducing waste does not always justify the necessary investments when viewed from a purely financial perspective. One of the reasons why firms are not more active in reducing waste is that many of the environmental costs are externalised. Recently, however, there has been a growing interest in making trans-

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parent the environmental impacts of the production and consumption of goods and services (Lebel and Lorek, 2008). Many businesses are seeking to demonstrate good corporate citizenship by measuring, reporting and addressing negative social and environmental impacts arising from their operations and product life cycles (Chapagain and Orr, 2009). The recent popularisation of carbon footprinting, disclosure and labelling are evidence of this. In addition, product environmental labelling initiatives in many jurisdictions are enabling consumers to become more aware of the impacts of their purchasing decisions and thereby take greater responsibility for their consumption patterns. Such developments are creating new incentives for reducing food waste. As one example, US foodservice provider Bon Appetit has announced a plan to cut food waste by 20% with the intention of cutting greenhouse gas emissions by more than 2000 t CO₂-eq yr⁻¹ (Environmental Leader, 2009). Another example, driven by public policy, is the Love Food Hate Waste campaign in the UK (www.lovefoodhatewaste.com).

Food that is not consumed or used in some other beneficial way represents a waste of all of the resources that were used in its production and distribution, such as water. As already mentioned, water availability is a critical concern to future food security and environmental sustainability. Our research concerns the mapping of food waste through the distribution and consumption stages of the product life cycle and the use of water footprinting to assess the impact on water resources. This case study focuses on the small and geographically well-defined Australian mango industry, having an average annual production of 44 692 t of marketable fresh fruit. To our knowledge, this is the first application of water footprinting to assess the impact of food waste on water resources. As noted by Yang and Zehnder (2007), water footprinting studies in the past have been overwhelmingly concerned with describing national and global-level virtual water flows in relation to international trade and have typically used crude statistics obtained from international databases. By using location specific data in this case study, we also seek to demonstrate the relevance of water footprinting in addressing local-scale problems regarding food production and water scarcity.

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2 Methodology and data

2.1 Mapping of food chain waste

Mangoes are an important tropical fruit, accounting for approximately 50% of all tropical fruits produced worldwide and with world production forecast to exceed 30 million t by 2010 (FAO, 2003). In contrast, the Australian mango industry is small, accounting for considerably less than 1% of world production, making it amenable to case study analysis. Although mango has been grown in Australia since early European settlement (mid 1800's), an organised industry formed in the late 1970's (Bally et al., 2000). The industry is mainly focussed on supplying fresh mango for Australian household consumption with lesser volumes exported to countries such as Singapore, Hong Kong, Malaysia, UAE and Japan. There are seven major growing regions (Table 1).

In this study, the food chain for Australian-grown fresh mango to Australian households was mapped. This food chain fluctuates significantly from year to year due mainly to the variability in local fresh mango production, which in recent years has ranged from 33 445 t (season 2005/06) to 59 985 t (season 2006/07). As such, averages were calculated over a six-year period, from season 2003/04 to season 2008/09, for which data were available. Industry representatives (Australian Mango Industry Association, Horticulture Australia Limited) provided data on the production of fresh and processing mangoes. Specifically, these data represent the shipment of marketable mangoes from the regional packing stations. Not included are mangoes grown but deemed unsalable, for which statistics are not collected in Australia. Data on the import and export of fresh mango were obtained from the World Trade Atlas (Global Trade Information Services, Inc.).

Data on retail sales of fresh mango were provided by Horticulture Australia Limited, based on retail scan data from one of Australia's national chain store retailers and household survey data describing the market share for the various retail distribution channels for fresh mango in Australia. The proportion of fresh mango sold to households and the food service sector was estimated at 85 and 15% respectively, based on

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advice from industry experts. The mass balance of fresh mango shipments from regional packing stations, imports, exports and sales to retail and food service was used to estimate waste in the distribution stage, taking into account weight losses of 5.4% (i.e. 0.2% per day over 27 days which is typical for the Australian fresh mango food chain, Macnish et al., 1997). In the consumer stage, avoidable waste was estimated at 26.3%, i.e. the same proportion of the weight of fruit that was found to be thrown away in a detailed UK study of household waste (WRAP, 2008). No equivalent study of household waste has been undertaken in Australia. Unavoidable waste (peel and stone) was estimated at 20% of consumed fruit.

2.2 Crop water requirements

For each of the major mango producing regions of Australia (Table 1), crop water requirements (mm yr^{-1}) and effective rainfall (mm yr^{-1}) were calculated using CropWat for Windows Version 4.3 (FAO, 1998), using climate data obtained from the New_LocClim local climate estimator (FAO, 2005). The use of locally relevant climate data overcomes a recognised weakness (Chapagain and Orr, 2009; Liu et al., 2007) of many previous water footprint studies which have used national average climate data, which especially for a large country like Australia may poorly represent local growing conditions. A second criticism is that many previous water footprint studies have assumed that crop water requirements have been fully met by supplementary irrigation, which is rarely the case and leads to an overestimation of consumptive water use (Chapagain and Orr, 2009). In contrast, for this study, the supplementary irrigation used in each major growing region was based on government sponsored irrigation surveys and grower recommendations (Barracough and Company, 1999; Ngo and Owens, 2002; DAFWA, 2003; NSW DPI, 2004; NT DPIFM, 2006; Johnson and Parr, 2007).

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2.3 Water footprint calculation

The virtual water content (VWC) of a product is the sum of all the water consumed in the various stages of production. This usually includes so-called blue water appropriated from surface and groundwater resources, green water which is rainfall consumed through crop evapotranspiration, and gray (or dilution) water, being the volume of freshwater needed to assimilate emissions to freshwater (Chapagain et al., 2006b). The VWC of Australian-grown fresh mango at the point of despatch from each major production region was calculated using average production statistics and the effective rainfall and supplementary irrigation data calculated above (Sect. 2.2). Gray water requirements were calculated based on nitrogen application at $3 \text{ kg t}^{-1} \text{ ha}^{-1}$ of fruit yield, losses to freshwater of 30% (NSW DPI, 2004) and using the US EPA's recommended limit for nitrate in drinking water of 10 mg l^{-1} (measured as nitrogen). In addition, $10 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ of water was estimated to be used in orchard operations (weed and pest control, flowering management) and 0.7 m^3 of water per t of fruit in post harvest operations (washing, application of fungicide and pesticide). Water use in the distribution and consumption stages of the product life cycle was considered to be negligible. For the purpose of apportioning water consumption between co-products, an economic allocation was used with 94% of the value of orchard production associated with the production of fresh mango and 6% with processing mangoes.

In the past, the water footprint of a product has been calculated in such a way that it is synonymous with the VWC (WFN, 2009). However, this approach to product water footprinting has been shown to be potentially misleading as it fails to differentiate adequately between irrigation water and natural rainfall that occurs over agricultural lands, despite the two having very different opportunity costs. In addition, there has generally been a failure to account for the local nature of freshwater scarcity (Ridoutt et al., 2009a, b). To report that the water footprint of a cup of coffee is 140 l or the water footprint of one kg of cheese is 5000 l (www.waterfootprint.org), gives no clear indication about the potential for harm from freshwater consumption. As such, the re-

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vised water footprint calculation method of Ridoutt and Pfister (2009; Fig. 1) was used in this study. This revised method considers freshwater consumption in the context of resource availability and enables quantitative comparisons between products and production stages in terms of their potential to contribute to freshwater scarcity. For this method, the impact of land use on blue water resources was calculated using a comparison to a forested ecosystem using the method of Zhang et al. (2001). It was assumed that in the absence of production, the mango orchard would eventually revert to a forest or open woodland. Local water stress characterisation factors for each major mango producing region were derived from the water stress index (WSI) of Pfister et al. (2009; Fig. 2). The WSI has a spatial resolution of 0.5 degrees and is more appropriate for describing water stress at a local watershed level than indicators based on national or per capita statistics.

3 Results

3.1 Distribution and consumption waste

Over the past six years, Australian mango growers have despatched an average of 44 692 t of fresh mango and 15 260 t of processing mango (Fig. 3). The latter represent mostly second grade mangoes, unmarketable as fresh fruit, which are used to make products such as juice and puree. Not all Australian mango growers are located in proximity to processing facilities, meaning that sale of the relatively low value processing fruit is often not viable. As such, considerable amounts of production waste are generated at the orchard stage, which we were unable to quantify. However, anecdotal evidence suggests that marketable fresh fruit may represent only around 40% of orchard production (AMIA, 2004), although this figure is certainly not representative of well managed orchards unless the harvest was damaged by severe weather conditions. In Australia, mangoes are grown in the sub-tropical and tropical northern regions, requiring transportation over vast distances to the major urban centres of Sydney, Mel-

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bourne and Brisbane. For example, the distance between the Mareeba growing region in Far North Queensland and Melbourne is around 2800 km. The distance between the Katherine growing region and Sydney is around 3600 km. The distribution channels for Australian fresh mango are also complex, potentially involving consolidators, wholesalers and brokers and a range of chain store and independent retailers, the latter mainly fruit shops (CDI Pinnacle, 2004). Taking into account the minor levels of imported and exported fresh mango, fruit weight loss (i.e. respiration and moisture content losses) and sales to the consumer and food service sectors, waste in the distribution stage was estimated at 14 709 t (Fig. 3). Avoidable waste of fresh mango by Australian households was estimated at 5642 t (Fig. 3).

3.2 Consumptive water use

The consumptive use of green water, being equivalent to the effective rainfall, ranged from 5800 m³ ha⁻¹ yr⁻¹ in Kununurra to 12 230 m³ ha⁻¹ yr⁻¹ in Northern New South Wales (Table 2; using the factor 10 to convert mm yr⁻¹ to m³ ha⁻¹ yr⁻¹). The consumptive use of blue water by supplementary irrigation ranged from 0 to 10 600 m³ ha⁻¹ yr⁻¹ depending on the growing region and was always less than the irrigation requirement calculated by the CropWat model to ensure crop water requirements were always fully met (Table 2). For example, a benchmarking survey of horticultural producers in Queensland found that the average irrigation water use by mango growers in the Mareeba district was 3700 m³ ha⁻¹ yr⁻¹ (Barraclough and Company, 1999, p. 51), equivalent to 370 mm yr⁻¹, and 327 mm yr⁻¹ or 47% lower than the calculated irrigation requirement (Table 2). In Northern New South Wales supplementary irrigation is not recommended, except in the orchard establishment phase (NSW DPI, 2004). Where supplementary irrigation is required, the critical time is during fruit development as water stress at this time can lead to reduced yields (Johnson and Parr, 2007). At other times of the year, growers often limit irrigation to prevent excessive vegetative growth (Kulkarni and Landon-Lane, 1992).

Evapotranspiration by mango orchards consumed 50 to 81% of precipitation depend-

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ing upon the growing region (Table 3). In contrast, the predicted evapotranspiration by forested ecosystems in these locations ranged from 61 to 89% of precipitation. As expected, the mango orchards intercepted less precipitation than the forested ecosystems they replaced (Scanlon et al., 2007; Rost et al., 2008). The exception was in Northern New South Wales where a positive difference of 51 mm yr^{-1} was predicted (Table 3), representing a consumptive use of freshwater due to reduced stream flow and/or groundwater recharge of $510 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.

At orchard gate (i.e. the point of despatch to market after harvesting, washing, application of fungicides and insecticides, etc.), the total VWC of Australia's fresh mango crop was 102.7 GJ (Table 4). The average proportions of green, blue and gray virtual water were 62, 33 and 5%, although this varied from one growing region to another. This represents the total volume of freshwater, from various sources, required to produce the average annual production of 44 692 t of fresh mango distributed across the major mango producing regions as described in Table 1. However, as described previously, not all of this consumptive water use has an impact on freshwater resource availability. The volumetric impact on blue water availability was 39.3 GJ and the water footprint, calculated using the water stress characterisation factors in Fig. 2, was 1.71 GJ (Table 4). The greatest contribution to the water footprint came from the production of fresh mango in the Burdekin/Townsville growing region (1.36 GJ or approximately 80% of the industry's water footprint). What this means is that around 80% of the Australian fresh mango growing industry's potential to contribute to water scarcity occurred through the production of fresh mango in the Burdekin/Townsville region. Although this region produced only 23.2% of Australia's fresh mango (Table 1), it had the second highest water stress characterisation factor (0.110, Fig. 2) and the second highest irrigation water use (680 mm yr^{-1} , Table 2).

3.3 Water footprint of mango food chain waste

As a consequence of avoidable food chain waste and fruit weight loss, the consumption of one kg of fresh mango by an Australian household was estimated to require

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1.36 kg to be purchased at the retail stage and 2.27 kg to be despatched from an orchard. As such, the VWC of one kg of Australian-grown fresh mango at the point of household consumption was 5218 l, made up of 2429, 1921 and 867 l associated with the consumed fruit, distribution waste and consumer waste respectively (Table 5). Similarly, the water footprint of Australian-grown fresh mango at the point of household consumption was 871 kg^{-1} , with 53% of the water footprint associated with distribution and consumption waste. The Australian-equivalent water footprint, derived by dividing the water footprint by the Australian average WSI (0.402) was 2171 kg^{-1} , meaning that the consumption of one kg of fresh mango by an Australian household has the same potential to contribute to freshwater scarcity as the direct consumption of 217 l of water in Australia.

Overall, waste in the food chain of Australian-grown fresh mango to Australian households represented an average annual waste of 26.7 GJ of green water resources and 16.6 GJ of blue water resources (Table 5). The water footprint of this waste was 0.72 GJ, comprising 0.50 GJ for the distribution waste and 0.22 GJ for the consumption waste. The corresponding Australian-equivalent water footprint of this waste was 1.80 GJ (Table 5), meaning that consumptive water use associated with waste in the food chain of Australian-grown fresh mango to Australian households has the same potential to contribute to freshwater scarcity as the direct consumption of 1.80 GJ of water in Australia.

4 Discussion

This study has provided further evidence to highlight the importance of food waste, with the finding that in the food chain of Australian-grown fresh mango to Australian households less than 50% of fruit despatched from the growing regions was ultimately consumed. Most important were the losses occurring in the distribution stage, estimated at almost 37% of fruit. Mangoes, which are an extremely perishable fruit, require careful postharvest handling, including temperature and disease control, to achieve acceptable retail shelf life, consistent ripening and good quality retail presentation. Poor

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practices can lead to entire consignments becoming unsalable by the time they reach the retailer (Ledger et al., 2003). As such, efforts are underway within the Australian mango industry to improve fruit transportation and ripening systems (Hennessy, 2008).

5 Avoidable losses occurring in the consumption stage were estimated at almost 17% of fruit, based on statistics from the UK (WRAP, 2008) which were deemed to be relevant to mango consumption in Australia. On the one hand, mango is more perishable than many other kinds of common fruits, such as apples and oranges, meaning that consumer wastage of mango is likely to be higher than the average. However, in Australia, mango is a special occasion fruit, usually consumed at home (McKinna, 2005),
10 and therefore perhaps less likely to be wasted than fruits purchased routinely, in larger quantities, and carried outside the home (e.g. in packed lunches). Further research is needed in Australia to more accurately define the composition of food waste, the causal factors and opportunities for reduction and diversion.

In Australia, very little waste in the mango food chain is likely to be recovered for
15 other beneficial purposes such as reprocessing and redistribution through charitable organisations, compositing or bioenergy production (Morgan, 2009). Welfare agencies have only recently begun to collect unsalable fresh fruit, vegetables and meat from supermarkets and this is occurring only on a limited scale (Godinho, 2009). Compared to the 65 000 t of organic waste sent to landfill by Woolworths, one of Australia's two
20 largest supermarket chains, the company diverted only 5354 t for renewable energy production in the 2007/08 financial year (Woolworths Limited, 2008).

Food chain waste has important implications for virtual water accounting. In this study, the VWC of one kg of Australian-grown fresh mango consumed by an Australian household increased from 2429 to 5218 l when distribution and consumption waste
25 were taken into consideration, which is more than a doubling (Table 5). These numbers compare with 3156 l kg⁻¹ reported in the often cited UNESCO-IHE report: Water Footprints of Nations (Chapagain and Hoekstra, 2004). However, as mentioned previously, these VWC values have the potential to be misleading because they fail to differentiate the source of the water used and the local water scarcity. Therefore, these

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figures give no indication of the potential to cause harm from consumptive water use. As such, the water footprint calculation method of Ridoutt and Pfister (2009) was used, as it enables a quantitative comparison between products in terms of their potential to contribute to water scarcity. The water footprint of one kg of Australian-grown mango
5 consumed by an Australian household was 87 l (Table 5), which compares to 141 l for a jar of Dolmio® pasta sauce (575 g) and 13 l for a bag of Peanut M&M's® (250 g; Ridoutt and Pfister, 2009).

The impact of mango production on water resources also varied regionally. This was evident when water footprint values were compared, as they ranged from 7.5 l kg⁻¹
10 (at orchard gate for the Mareeba growing region) to 132 l kg⁻¹ (Burdekin/Townsville growing region), which is almost an 18-fold difference in the potential to contribute to water scarcity. As such, efforts to improve water use efficiency in mango orchards would deliver the greatest benefits if first targeted to the Burdekin/Townsville region. However, variability in water use efficiency between individual growers, which is also
15 understood to be high (Growcom, 2004), would also need to be taken into account.

From a global perspective, one of the greatest challenges is to meet future food demands within the constraints of sustainable freshwater consumption. The enormity of this challenge arises from the fact that freshwater has already become a scarce and overexploited natural resource in many parts of the world, including parts of Australia.
20 At a practical level, the impact of food consumption patterns on global freshwater resources must become less intense. Product water footprints, which describe the potential of a product to contribute to water scarcity, must therefore be progressively reduced. In this regard, we have considered the likely effectiveness of food chain waste reduction as a strategy for reducing product water footprints and a comparison was made
25 with other potential measures.

In a scenario where distribution and consumption waste were each halved, the water footprint of one kg of Australian-grown fresh mango consumed by an Australian household would be reduced from 87 to 57 l, which is a reduction of 34%. Similarly, the Australian-equivalent water footprint would be reduced from 217 to 142 l, a sav-

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ing equivalent to 74l of direct water consumption for every one kg of fresh mango consumed. In comparison, a detailed benchmarking study of irrigation water use in Queensland identified a gap of 40% between best water use efficiency in mango orchards and average practice (Barraclough and Company, 1999). In a second scenario where irrigation water use was reduced by 40% across half of Australia's mango orchard estate (while maintaining the same yields), the water footprint of one kg of Australian-grown fresh mango consumed by an Australian household would be reduced from 87 to 72l, which is a reduction of 18%. This saving would be equivalent to 38l of direct water use for every one kg of fresh mango consumed. Since the Australian mango industry is in a growth phase (AMIA, 2004), another strategy might involve deliberate expansion in regions where freshwater is most abundant and where irrigation water use will have the least potential to contribute to water scarcity. In a third scenario where the industry expanded by 20% with that growth occurring in the Darwin and Katherine regions (WSI 0.010, Fig. 2), the average water footprint of one kg of Australian-grown fresh mango consumed by an Australian household would be reduced from 87 to 77l, or 11%.

These three scenarios are admittedly simplistic and deserve further careful consideration and analysis. However, they do serve to confirm that reducing food chain waste is an important strategy for alleviating the pressure of food consumption on freshwater resources. Interventions to reduce food chain waste will likely have as great or even greater impact on freshwater resource availability as other possible strategies, such as improving irrigation water use efficiency. Hence, an escalation in efforts to reduce food chain waste is essential.

5 Conclusions

The point has been well made that food waste is also a waste of precious water resources (Lundqvist et al., 2008; Nellemann et al., 2009). However, until a link is established between specific waste streams and the local water resources that are be-

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ing adversely impacted there is little empowerment for action. While water resources can be discussed in terms of national or global averages, the consequences of water scarcity, being resource depletion and damage to human health and ecosystem quality (Pfister et al., 2009; Ridoutt et al., 2009b), are experienced at the local watershed level. What this case study of the mango food chain in Australia has shown is that product water footprinting can be used to make this waste of water transparent and meaningful in the context of local water resource availability. This transparency is critical if food waste is to be seen not simply in terms of its private economic cost, but in terms of the wider social and environmental impacts, and thereby create a case for government intervention as well as corporate and personal action on the grounds of social responsibility. A further complication is the increasing connectedness of global food chains, meaning that water resource impacts may occur far from where consumption and food chain waste is occurring. We therefore concur with Chapagain and Orr (2009, p. 1227) who argue that, "The *local* character of a product's virtual water content must be made more transparent through the supply chain in order to better understand the impacts of distant consumption on local water resources" (emphasis added). At present, the extent to which the local consumption and waste of food products is intervening in the hydrological cycle throughout the world is rarely understood or appreciated.

Traditionally, water resources planning and management has focussed on increasing supply and where supply has become limited the shift has been to demand management, usually in relation to direct consumption by the industrial, domestic and agricultural sectors. In future, these efforts need to be complemented by strategies which take into consideration indirect (or virtual) water consumption. At the consumer level, indirect water use through the consumption of food and other goods and services is far greater than direct water use, representing perhaps 90% of an individual's burden on freshwater resources (Molden et al., 2007). Ultimately, it is the demand for goods and services that creates the demand for consumptive water use in the industrial and agricultural sectors.

Food waste is ubiquitous, occurring at all stages of the food chain. Therefore, a large

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and diverse group of stakeholders need to be made aware of the consequences of food waste on water resources and subsequently engaged in efforts to reduce food chain waste. Overcoming the social, political and technological barriers which cause food chain waste to persist will be important. In order to address the unsustainable use of global freshwater resources and meet the food production requirements of a growing world population, food chains must become much more efficient in terms of consumptive water use. For the Australian mango food chain, our analysis indicated that reducing waste was indeed an effective way of reducing impacts on freshwater resources relative to other water efficiency measures. However, this conclusion might vary from one food chain to another and a widespread adoption of product water footprinting by the agriculture and food industries is encouraged to underpin priority setting.

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References

- AMIA (Australian Mango Industry Association): Mango Industry Strategic Plan, online available at: <http://www.horticulture.com.au/librarymanager/libs/45/Mango%20Strategic%20Plan.pdf>, (last access: May 2009), 2004.
- Barraclough & Co.: Audit of water & irrigation use efficiencies on farms within the Queensland horticultural industry, online available at: http://www.nrw.qld.gov.au/services_resources/item_details.php?item_id=31059, (last access: May 2009), 1999.
- Bally, I. S. E., Johnson, P. R., and Kulkarni, V. J.: Mango production in Australia, *Acta Hort.*, 509, 59–67, 2000.
- Bartram, J.: Improving on haves and have-nots, *Nature*, 452, 7185, 283–284, 2008.
- Bloom, J.: The food not eaten. Food waste: out of sight, out of mind, *Culinate*, Portland, OR, USA, online available at: http://www.culinate.com/articles/features/wasted_food, (last access: May 2009), 2007.

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- CDI Pinnacle: Horticulture value chain analysis and policy development, online available at: http://www.growcom.com.au/_uploads/16348Submission_Horticultural_Value_Chain_Analysis.pdf, (last access: May 2009), 2004.
- Chapagain, A. K., and Hoekstra, A. Y.: Water footprints of nations, *Value of Water Research Report Series No.16*, UNESCO-IHE, Delft, The Netherlands, 2004.
- Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. G.: Water saving through international trade of agricultural products, *Hydrol. Earth Syst. Sci.*, 10, 455–468, 2006a, <http://www.hydrol-earth-syst-sci.net/10/455/2006/>.
- Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., and Gautam, R.: The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries, *Ecol. Econ.*, 60(1), 186–203, 2006b.
- Chapagain, A. K. and Orr, S.: An improved water footprint methodology linking global consumption to local water resources: A case study of Spanish tomatoes, *J. Environ. Manage.*, 90(2), 1219–1228, 2009.
- DAFWA (Department of Agriculture and Food Western Australia): Irrigation Calculator, ver. 4.0, online available at: http://www.agric.wa.gov.au/content/lwe/water/irrig_calculator_nlantzke.htm, (last access: May 2009), 2003.
- Environmental Leader: Foodservice firm buys less beef, cheese, tropical fruit to cut carbon impact, online available at: <http://www.environmentalleader.com/2009/04/06/foodservice-firm-buys-less-beef-cheese-tropical-fruit-to-cut-carbon-impact/>, (last access: May 2009), 2009.
- Falkenmark, M.: Water and sustainability: A reappraisal, *Environment*, 50(2), 4–16, 2008.
- Falkenmark, M. and Lannerstad, M.: Consumptive water use to feed humanity – curing a blind spot, *Hydrol. Earth Syst. Sci.*, 9, 15–28, 2005, <http://www.hydrol-earth-syst-sci.net/9/15/2005/>.
- FAO: CropWat for Windows, version 4.3, online available at: http://www.fao.org/nr/water/infoces_databases_cropwat.html, (last access: May 2009), 1998.
- FAO: Medium-term prospects for agricultural commodities, online available at: <http://www.fao.org/docrep/006/y5143e/y5143e00.htm>, (last access: May 2009), 2003.
- FAO: New_LocClim Local Climate Estimator, online available at: http://www.fao.org/nr/climpag/pub/en3_051002_en.asp, (last access: May 2009), 2005.
- FAO: Number of hungry people rises to 963 million, online available at: <http://www.fao.org/>

5102

- news/story/en/item/8836/, (last access: May 2009), 2008a.
- FAO: The state of food insecurity in the world, online available at: <http://www.fao.org/docrep/011/i0291e/i0291e00.htm>, (last access: May 2009), 2008b.
- Godinho, M.: Let's waste not while others are wanting, in: *The Age*, Melbourne, Australia, 1 May 2009.
- 5 Growcom: Benchmark – irrigating mangoes, Water for Profit Fact Sheet, Growcom, Fortitude Valley, Queensland, Australia, 2004.
- Hennessy, C.: Implementing a top end better mangoes project, in: *Mango Industry Report 07/08*, Australian Mango Industry Association, Mareeba, Australia, 2008.
- 10 Henningsson, S., Hyde, K., Smith, A., and Campbell, M.: The value of resource efficiency in the food industry: A waste minimisation project in East Anglia, UK, *J. Clean Prod.*, 12(5), 505–512, 2004.
- Johnson, P. R. and Parr, D.: Mango growing in Western Australia, online available at: http://www.agric.wa.gov.au/content/hort/fn/cp/pawpaws/b4348_index.htm, (last access: May 2009), 2007.
- 15 Kader, A. A.: Increasing food availability by reducing postharvest losses of fresh produce, *Acta Hortic.*, 682, 2169–2175, 2005.
- Kulkarni, V. J. and Landon-Lane, C.: Report on mango growers' survey, Technical Bulletin 183, Northern Territory Department of Primary Industries and Fisheries, Darwin, Australia, 1992.
- 20 Lebel, L. and Lorek, S.: Enabling sustainable production-consumption systems, *Ann. Rev. Environ. Resour.*, 33, 241–275, 2008.
- Ledger, S. N., Campbell, T. P., Holmes, R. J., Kernot, I. I., and Hofman, P. J.: Improving knowledge and practices in mango supply chains, in: *Proceedings of the Australian Postharvest Horticulture Conference*, Brisbane, Australia, 1–3 October, 2003, 77–79, 2003.
- 25 Liu, J. and Savenije, H. H. G.: Food consumption patterns and their effect on water requirement in China, *Hydrol. Earth Syst. Sci.*, 12, 887–898, 2008, <http://www.hydrol-earth-syst-sci.net/12/887/2008/>.
- Liu, J. G., Yang, H., and Savenije, H. H. G.: China's move to higher-meat diet hits water security, *Nature*, 454, 7203, p. 397, 2008.
- 30 Liu, J. G., Zehnder, A. J. B., and Yang, H.: Global consumptive water use for crop production: The importance of green water and virtual water, *Water Resour. Res.*, 45, W05428, doi:10.1029/2007WR006051, 2009.
- Liu, J. G., Zehnder, A. J. B., and Yang, H.: Historical trends in China's virtual water trade, *Water*

5103

- Int.*, 32(1), 78–90, 2007.
- Lundqvist, J., Barron, J., Berndes, G., Bertell, A., Falkenmark, M., Karlberg, L., and Rockström, J.: Water pressure and increases in food & bioenergy demand implications of economic growth and options for decoupling, in: *Scenarios on Economic Growth and Resource Demand*, Swedish Environmental Advisory Council, Ministry of the Environment, Stockholm, Sweden, 2007.
- 5 Lundqvist, J., de Fraiture, C., and Molden, D.: Saving water: From field to fork, SIWI Policy Brief, Stockholm International Water Institute, Stockholm, Sweden, 2008.
- Macnish, A. J., Joyce, D. C., and Hetherington, S. E.: Packaging to reduce water loss can delay ripening of mango (*Mangifera indica* L. cv. "Kensington Pride") fruit, *Aust. J. Exp. Agr.*, 37(4), 463–467, 1997.
- McKinna, D.: Australian mango industry: Consumer market research, usage & attitude, purchasing & consumption, Horticulture Australia Limited, Sydney, Australia, 2005.
- 15 Meeusen, M. and Hagelaar, G.: Food losses: what do stakeholders think? A study of perception, attitude and behaviour of stakeholders to prevent food losses, Report 2008-014, Landbouw-Economisch Instituut, Den Haag, The Netherlands, 2008.
- Molden, D., de Fraiture, C., and Rijsberman, F.: Water scarcity: The food factor, *Issues Sci. Technol.*, 23(4), 39–48, 2007.
- Morgan, E.: Fruit and vegetable consumption and waste in Australia, Victorian Health Promotion Foundation, Carlton South, Australia, 2009.
- 20 Nellemann, C., MacDevette, M., Manders, T., Eickhout, B., Svihus, B., Prins, A. G., and Kaltenborn, B. P. (Eds.): The environmental food crisis: The environment's role in averting future food crises, UNEP rapid response assessment, United Nations Environment Programme, UNEP/GRID-Arendal, Arendal, Norway, 2009.
- 25 NSW DPI (New South Wales Department of Primary Industries): *Mango Growing*. Agfact H6.1.10, fourth edition, NSW Centre for Tropical Horticulture, Alstonville, Australia, 2004.
- Ngo, H. and Owens, G.: The profitability of mangoes in the top end, Technical Bulletin 301, Northern Territory Government Department of Business, Industry & Resource Development, Darwin, Australia, 2002.
- 30 NT DPIFM (Northern Territory Department of Primary Industry, Fisheries and Mines): *Growing Note FG8 – Mango*, online available at: http://www.nt.gov.au/d/Content/File/p/Fruit/FG8_mango.pdf, (last access: May 2009), 2006.
- Pagan, B. and Prasad, P.: The Queensland food eco-efficiency project: Reducing risk and

5104

- improving competitiveness, *J. Clean Prod.*, 15(8–9), 764–771, 2007.
- Pfister, S., Koehler, A., and Hellweg, S.: Assessing the environmental impacts of freshwater consumption in LCA, *Environ. Sci. Technol.*, 43(11), 4098–4104, 2009.
- Ridoutt, B. G., Eady, S. J., Sellahewa, J., Simons, L., and Bektash, R.: Water footprinting at the product brand level: case study and future challenges, *J. Clean Prod.*, 17(13), 1228–1235, 2009a.
- Ridoutt, B. G., Eady, S. J., Sellahewa, J., Simons, L., and Bektash, R.: Product water footprinting: How transferable are the concepts from carbon footprinting? In: *Proceedings of the 6th Australian Conference on Life Cycle Assessment: Sustainability Tools for a New Climate*, Melbourne, Australia, 16–19 February 2009b.
- Ridoutt, B. G. and Pfister, S.: A new approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity, *Global Environ. Chang.*, in review, 2009.
- Rockström, J.: Water for food and nature in drought-prone tropics: Vapour shift in rain-fed agriculture, *Philos. T. Roy. Soc. B*, 358, 1440, 1997–2009, 2003.
- Rockström, J. and Barron, J.: Water productivity in rainfed systems: Overview of challenges and analysis of opportunities in water scarcity prone savannahs, *Irrigation Sci.*, 25(3), 299–311, 2007.
- Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: The potential of green water for increasing resilience to global change, *Water Resour. Res.*, 45, W00A12, doi:10.1029/2007WR006767, 2009.
- Rockström, J., Lannerstad, M., and Falkenmark, M.: Assessing the water challenge of a new green revolution in developing countries, *P. Natl. Acad. Sci. USA*, 104(15), 6253–6260, 2007.
- Rost, S., Gerten, D., and Heyder, U.: Human alterations of the terrestrial water cycle through land management, *Adv. Geosci.*, 18, 43–50, 2008, <http://www.adv-geosci.net/18/43/2008/>.
- Scanlon, B. R., Jolly, I., Sophocleous, M., and Zhang, L.: Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality, *Water Resour. Res.*, 43(3), W03437, doi:10.1029/2006WR005486, 2007.
- UNESCO-WWAP: *Water: A Shared Responsibility: The United Nations World Water Development Report 2*, United Nations Educational Scientific and Cultural Organization-World Water Assessment Programme, Paris, France, 2006.
- WFN (Water Footprint Network): *Glossary – Water Footprint*, online available at: [www.](http://www.waterfootprint.org/)

5105

- waterfootprint.org/?page=files/DefinitionWaterFootprint, (last access: February 2009), 2009.
- Woolworths Limited: *Corporate Responsibility Report 2008*, online available at: http://crreport08.woolworthslimited.com.au/about_woolworths.php, (last access: May 2009), 2008.
- WRAP (Waste and Resources Action Programme): *The Food We Waste*, online available at: http://www.wrap.org.uk/downloads/The_Food_We_Waste_v2_2_3e1bd9e2.5635.pdf, (last access: May 2009), 2008.
- Yang, H., Wang, L., Abbaspour, K. C., and Zehnder, A. J. B.: Virtual water trade: an assessment of water use efficiency in the international food trade, *Hydrol. Earth Syst. Sci.*, 10, 443–454, 2006, <http://www.hydrol-earth-syst-sci.net/10/443/2006/>.
- Yang, H. and Zehnder, A.: “Virtual water”: An unfolding concept in integrated water resources management, *Water Resour. Res.*, 43, W12301, doi:10.1029/2007WR006048, 2007.
- Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean evapotranspiration to vegetation changes at catchment scale, *Water Resour. Res.*, 37(3), 701–708, 2001.

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Table 1. Major mango producing regions in Australia.

Region	Production (tyr ⁻¹) ^a	%
Burdekin/Townsville, Queensland	12 737	23.2
Mareeba, Queensland	18 563	33.8
Bundaberg, Queensland	2 100	3.8
Northern New South Wales	800	1.5
Darwin, Northern Territory	12 792	23.3
Katherine, Northern Territory	6 430	11.7
Kununurra, Western Australia	1 470	2.7
Total	54 893	100

^a Based on 2004/05 season. Source: Australian Mango Industry Association and Northern Territory Government, Department of Regional Development, Primary Industry, Fisheries and Resources.

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Table 2. Crop water requirements for Australian mango.

Region	Crop water requirement (mm yr ⁻¹) ^a	Effective rainfall (mm yr ⁻¹) ^a	Irrigation requirement (mm yr ⁻¹) ^a	Recommended irrigation (mm yr ⁻¹) ^b
Burdekin/Townsville, Queensland	1679	765	914	680
Mareeba, Queensland	1664	1053	697	370
Bundaberg, Queensland	1570	866	703	400
Northern New South Wales	1288	1223	215	0
Darwin, Northern Territory	1989	915	1142	438
Katherine, Northern Territory	1932	671	1266	438
Kununurra, Western Australia	2045	580	1466	1060

^a CropWat for Windows ver. 4.3 (FAO, 1998);

^b Source: Barraclough and Co (1999), Ngo and Owens (2002), DAFWA (2003), NSW DPI (2004), NT DPIFM (2006), Johnson and Parr (2007).

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Table 3. Impact of land use on blue water resources: comparison of mango growing with a forest ecosystem.

Region	Precipitation (mm) ^a	Mango		Forest		Difference (mm)
		Effective rainfall (mm) ^b	Loss (%)	ET (mm) ^c	Loss (%)	
Burdekin/Townsville, Queensland	1040	765	74	867	83	-102
Mareeba, Queensland	2123	1053	50	1289	61	-236
Bundaberg, Queensland	1069	866	81	885	83	-18
Northern New South Wales	1708	1223	72	1172	69	51
Darwin, Northern Territory	1684	915	54	1164	69	-249
Katherine, Northern Territory	956	671	70	816	85	-145
Kununurra, Western Australia	778	580	75	695	89	-115

^a New_LocClim Local Climate Estimator (FAO, 2005);

^b CropWat for Windows ver. 4.3 (FAO, 1998);

^c Evapotranspiration (ET) for a forested ecosystem calculated using the method of Zhang et al. (2001).

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Table 4. Virtual water content (VWC, Gt) of Australian mango production (at orchard gate) based on an average annual production of 44 692 t distributed across the major mango producing regions as described in Table 1. The land use impact, blue water impact and water footprint (WF, all Gt) were calculated following the method of Ridoutt and Pfister (2009). The water footprint calculation uses the Water Stress Index (WSI) of Pfister et al. (2009; Fig. 2).

Region	Green VWC	Blue VWC	Gray VWC	Total VWC	Land use impact	Blue water impact	WF
Burdekin/Townsville, Queensland	12.6	11.2	1.2	25.0	0	12.4	1.36
Mareeba, Queensland	25.3	8.9	1.7	36.0	0	10.6	0.11
Bundaberg, Queensland	2.4	1.1	0.2	3.6	0	1.3	0.016
Northern New South Wales	1.3	<0.1	<0.1	1.3	<0.1	0.1	0.014
Darwin, Northern Territory	15.2	7.3	1.2	23.6	0	8.5	0.086
Katherine, Northern Territory	5.6	3.7	0.6	9.8	0	4.3	0.043
Kununurra, Western Australia	1.1	2.0	0.1	3.3	0	2.1	0.076
Total Australian production	63.4	34.2	5.1	102.7	<0.1	39.3	1.71

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Table 5. Virtual water content (VWC), blue water impact, water footprint (WF) and Australian-equivalent water footprint of Australian grown fresh mango consumed by Australian households.

	One kg of Australian-grown fresh mango consumed by an Australian household				Annual consumption of Australian-grown fresh mango by Australian households			
	Blue water		WF (l)	WF (Aust-eq) (l)	Blue water		WF (Gl)	WF (Aust-eq) (Gl)
	VWC (l)	impact (l)			VWC (Gl)	impact (Gl)		
Consumed fruit	2429	931	41	101	37.7	14.4	0.63	1.56
Distribution waste	1921	736	32	80	29.8	11.4	0.50	1.24
Consumer waste	867	332	14	36	13.5	5.2	0.22	0.56
Total	5218	1999	87	217	81.0	31.0	1.35	3.36

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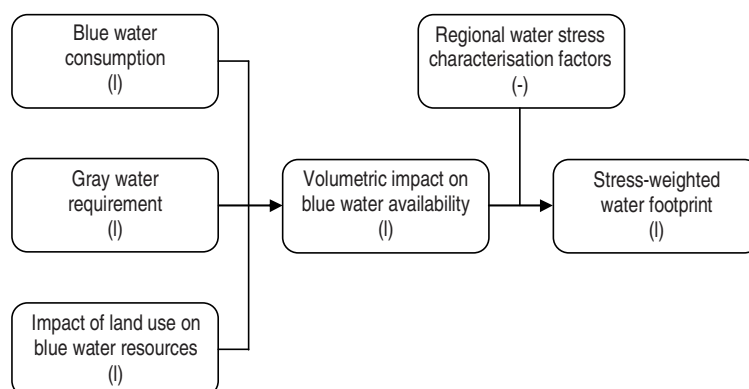


Fig. 1. Revised method of calculating product water footprints incorporating water stress characterisation factors (Ridoutt and Pfister, 2009).

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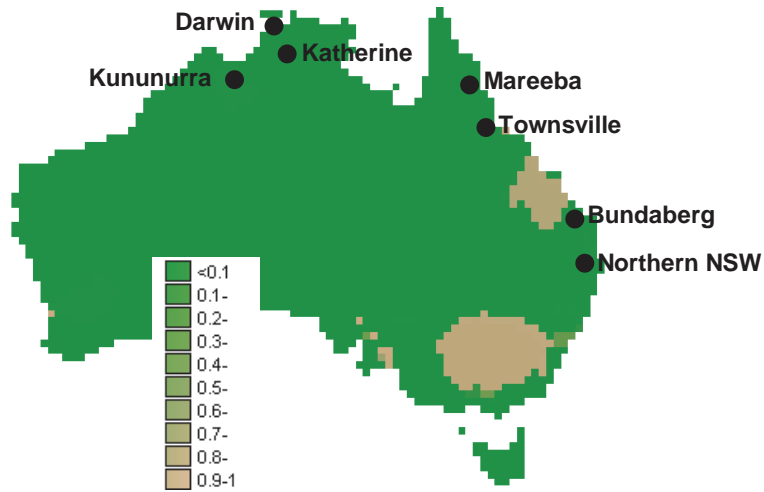


Fig. 2. Map of the Water Stress Index (WSI) for Australia (Pfister et al., 2009) showing the major mango producing regions.

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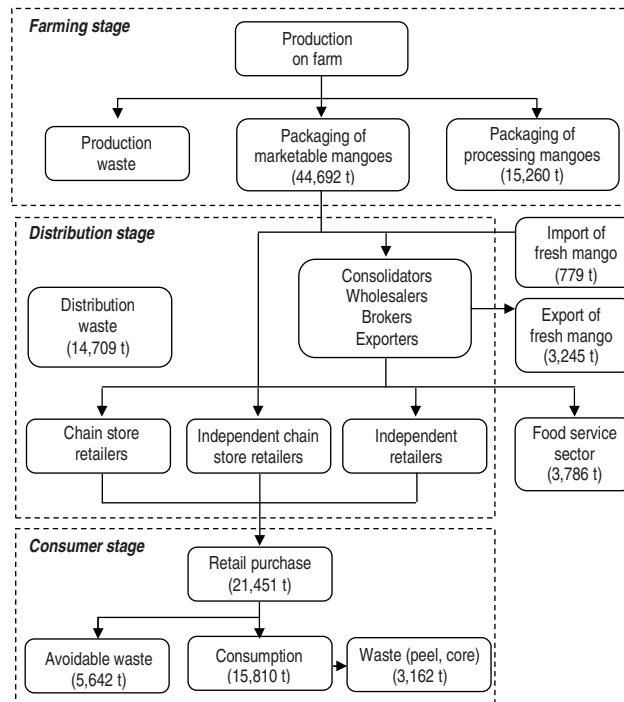


Fig. 3. Food chain for Australian-grown fresh mango to Australian households highlighting distribution and consumption waste.

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